BROOD-YEAR 2010 WINTER CHINOOK JUVENILE PRODUCTION INDICES WITH COMPARISONS TO JUVENILE PRODUCTION ESTIMATES DERIVED FROM ADULT ESCAPEMENT

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Brood-year 2010 Winter Chinook juvenile Production Indices with Comparisons to Juvenile Production Estimates Derived from Adult Escapement

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Abstract.— Brood-year 2010 juvenile winter-run Chinook salmon passage at Red Bluff Diversion Dam (RBDD) was 1,281,778 fry and pre-smolt/smolts combined, representing a juvenile cohort replacement rate of 0.88 from 2007. We compared rotary-screw trap fry-equivalent juvenile production indices (JPI's) to fry-equivalent juvenile production estimates (JPE's) derived using the National Oceanic and Atmospheric Administration's National Marine Fisheries Service JPE model. The JPE model uses estimates of adult escapement from the winter-run Chinook salmon carcass survey as the primary variate. The fry-equivalent rotary trap JPI for brood-year 2010 was 1,566,507. The 90% confidence intervals (CI) around the estimate were 988,163 (lower) and 2,144,851 (upper). The brood-year 2010 NMFS JPE was 1,049,385 and fell within the 90% CI about the rotary trap JPI; exceeding the lower 90% value by approximately 61,000 juveniles. Rotary-screw trap JPI's continued to be correlated strongly in trend when compared to carcass survey JPE's (r^2 = 0.84, P < 0.001, df = 12). No significant difference was detected between rotary trap JPI's and carcass survey JPE's (t = -0.63, P = 0.54, df = 12).

Egg to fry survival rates were estimated using adult escapement, fecundity data and the rotary trap JPI. The calculated 13-year *average* egg to fry survival rate was identical to the 25% static value input into the NMFS JPE model. In 2010 however, the JPI egg to fry survival value was estimated at 37%, in excess of one standard deviation of the 13-year average. Winter run Chinook salmon spawning in the highly regulated (e.g., flow, temperature and gravel augmentation) Sacramento River system should, at times, see very high levels of recruitment success or spawning efficiency in the absence of density dependent factors.

Overall, the relationship between the direct measure of juvenile abundance (JPI) and the indirect or modeled approach using carcass survey data remains strong. The addition of the 2010 data continues to support this relationship.

Table of Contents

List of Tables

Table **Page**

List of Figures

Figure **Page**

List of Figures continued

Introduction

Winter-run Chinook salmon is one of four distinct "runs" of Chinook salmon *(Oncorhynchus tshawytscha)* present in the upper Sacramento River, California. Distinguished by the season of the returning adult spawning migration, the winter-run Chinook salmon begin their return from the ocean to the Sacramento River in December (Vogel and Marine 1991).

Winter-run Chinook salmon have been federally listed as an endangered species since 1994[1]. Numerous measures have been implemented to protect and conserve the endangered winter-run Chinook salmon. One protective measure is adaptively managing water exports from the Central Valley Project's Tracy Pumping Plant and the State Water Project's Harvey Banks Delta Pumping Plant in the Sacramento-San Joaquin Delta (Delta). Exports are managed to limit entrainment of juvenile winter-run Chinook salmon (hereafter referred to as winter Chinook) annually migrating through the Delta seaward. The United States Bureau of Reclamation (USBR) and the California Department of Water Resources are authorized by the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) for incidental take of up to two percent of the annual winter Chinook population estimated to be entering the Delta and recovered at the pumping facilities (CDFG 1996). The NMFS uses a juvenile production model to estimate abundance of the juvenile winter Chinook population (JPE) entering the Delta. Historically, the model has used adult escapement estimates derived from Red Bluff Diversion Dam (RBDD) fish ladder counts (Diaz-Soltero 1995, 1997; Lecky 1998, 1999, 2000), but currently uses escapement estimates derived from the winter Chinook carcass survey (McInnis 2002, NMFS 2009).

The NMFS juvenile production model uses estimated adult escapement as the primary variate. One factor associated with inaccuracies of modeling juvenile production is the estimate of female spawners, the second variate of the JPE model. For the carcass survey, the size composition of fish sampled often leads to skewed sex ratios. Adult females are generally larger and may be more easily recognized and recovered than their male counterparts (Boydstun 1994, Zhou 2002). For example, in 1998, 1999, and 2000 the winter Chinook carcass survey male to female ratio was 1:8.9, 1:8.4, and 1:5.0, respectively (Snider et al 2001). Between 2001 and 2010, the average ratio of natural origin males to females was reported as 1:2.7 (USFWS 2011). Moreover, currently used carcass survey methodologies rely on several untested assumptions resulting in errors in estimation affecting both the accuracy and precision of annual adult estimates (USFWS 2011).

[1] The National Marine Fisheries Service first listed Winter-run Chinook salmon as threatened under the emergency listing procedures for the ESA (16 U.S.C.R. 1531-1543) on August 4, 1989 (54 FR 32085). A proposed rule to add winter Chinook salmon to the list of threatened species beyond expiration of the emergency rule was published by the NMFS on March 20, 1990 (55 FR 10260). Winter Chinook salmon were formally added to the list of federally threatened species by final rule on November 5, 1990 (55 FR 46515), and they were listed as a federally endangered species on January 4, 1994 (59 FR 440). Critical habitat for winter Chinook salmon has been designated from Keswick Dam (RM 302) to the Golden Gate Bridge (58 FR 33212; June 16, 1993). Winter Chinook salmon have been listed as endangered under the CESA since September 22, 1989 (California Code of Regulations, Title XIV, Section 670.5). Their federal endangered status was reaffirmed in June 2005 (70 FR 37160).

In light of the technical difficulties in estimating adult escapement described above, the use of the JPE model may be subject to considerable uncertainty. Estimated escapement is just one factor affecting the accuracy of JPE's. Another factor, not addressed directly in the JPE model, is success on the spawning grounds. Many adult salmon may return to spawn, but spawning and rearing habitat conditions vary between years and, at times, may not be favorable for successful reproduction (Heming 1981, Reiser and White 1988, Botsford and Brittnacher 1998). The overall result being the production of fewer juveniles than the JPE model would predict. Conversely, low adult abundance (i.e., no density dependent effects) or variable spawning habitat conditions may contribute to high survivorship of eggs and alevins in any given year. The use of a static juvenile survival rate, the sixth variate in the JPE model, may introduce or compound considerable error resulting in further juvenile production estimate inaccuracies.

The United States Fish and Wildlife Service (USFWS) has conducted direct monitoring of juvenile winter Chinook passage at RBDD since 1994. Martin et al. (2001) developed quantitative methodologies for indexing juvenile passage using rotary-screw traps. The USFWS rotary trap juvenile production indices (JPI's) have been used in support of production estimates generated from escapement data using the JPE model. Martin et al. (2001) stated that RBDD was an ideal location to monitor juvenile winter Chinook production because (1) the spawning grounds occur almost exclusively above RBDD (Vogel and Marine 1991; Snider et al. 1997, USFWS 2011), (2) multiple traps could be attached to the dam and sample simultaneously across a transect, and (3) operation of the dam could control channel morphology and hydrological characteristics of the sampling area providing for consistent sampling conditions for purposes of measuring juvenile passage.

The objectives of this study were to (1) estimate the abundance of brood year (BY) 2010 juvenile winter Chinook passing RBDD, (2) define temporal patterns of abundance, and (3) determine if JPI's from rotary trapping support JPE's generated from carcass survey data.

This annual report addresses, in detail, our juvenile winter Chinook monitoring activities at RBDD for the period July 1, 2010 through June 30, 2011. This report includes JPI's for the complete 2010 brood-year emigration period and will be submitted to the California Department of Fish and Game to comply with contractual reporting requirements for Ecosystem Restoration Program Grant Agreement Number P0685507 and to the US Bureau of Reclamation who funded a portion of the year's survey.

Study Area

The Sacramento River is the largest river system in California, flowing south through 600 kilometers (km) of the state (Figure 1). It originates in Northern California near Mt. Shasta as a mountain stream, widens as it drains adjacent slopes of the Coast, Klamath, Cascade, and Sierra Nevada mountain ranges, and reaches the ocean at the San Francisco Bay. Although agricultural and urban development have impacted the river, the upper river remains mostly unrestricted below Keswick Dam and supports areas of intact riparian vegetation. In contrast, urban and agricultural development has impacted much of the river between Red Bluff and San Francisco Bay. Impacts include, but are not limited to, channelization, water diversion, agricultural and municipal run-off, and loss of associated riparian vegetation.

Red Bluff Diversion Dam is located at river-kilometer 391 (RK 391) on the Sacramento River, approximately 3 km southeast of the city of Red Bluff, California. The dam is 226 meters (m) wide and composed of eleven, 18 m wide fixed-wheel gates. Between gates are concrete piers 2.4 m in width. The USBR's dam operators are able to raise the RBDD gates allowing for run-of-the-river conditions or lower them to impound and divert river flows into the Tehama-Colusa Canal. USBR operators generally raise the RBDD gates from September 16 through May 14 and lower them May 15 through September 15 of each year. As of the spring of 2009, the RBDD gates can no longer be lowered prior to June 15 and are raised by the end of August or earlier (NMFS 2009) in an effort to reduce the impact to spring Chinook salmon and green sturgeon (*Acipenser medirostris*).

Methods

Sampling gear.—Sampling was conducted along a transect using four 2.4 m diameter rotary-screw traps (E.G. Solutions® Corvallis, Oregon) attached via aircraft cables directly to RBDD. The horizontal placement of rotary traps across the transect varied throughout the study but generally sampled in river-margin (east and west river-margins) and mid-channel habitats simultaneously (Figure 2). Rotary traps were positioned within these *spatial zones* unless sampling equipment failed, river depths were insufficient (< 1.2 m), or river hydrology restricted our ability to sample with all traps (water velocity < 0.6 m/s).

Sampling regimes.—In general, rotary traps sampled continuously throughout 24-hour periods and were sampled once daily. During periods of high winter Chinook abundance, elevated river flows, or heavy debris loads, traps were sampled multiple times per day, continuously, or at random periods to reduce incidental mortality. When abundance of winter Chinook was very high, sub-sampling protocols were implemented to reduce take and incidental mortality in accordance with NMFS Section 10 research permit terms and conditions. The specific sub-sampling protocol implemented was contingent upon the number of winter Chinook captured or the probability of successfully sampling various river conditions. Typically, rotary traps were structurally modified to only sample one-half of the normal volume of water (Gaines and Poytress 2004). If further reductions in capture were needed, we decreased the number of traps sampling from four to three. During storm events and associated elevated river discharge levels, each 24 hour sampling period was divided into four or six non-overlapping strata and one or two strata was randomly selected for sampling (Martin et al 2001). Estimates were extrapolated to un-sampled strata by dividing catch by the strata-selection probability (i.e., P = 0.25 or 0.17). If further reductions in impact were needed or river conditions were intolerable sampling was not conducted.

Data collection.—All fish captured were anesthetized, identified to species, and enumerated with fork lengths (FL) measured to the nearest millimeter (mm). When capture of winter Chinook juveniles exceeded approximately 200 fish/trap, a random sub-sample of the catch was taken to include approximately 100 individuals, with all additional fish being enumerated and recorded. Chinook salmon race was assigned using length-at-date criteria developed by Greene[2] (1992). Other data were collected at each trap sampling and included: length of time trap sampled, velocity of water immediately in front of the cone at a depth of 0.6 m, and depth of cone "opening" submerged. Water velocity was measured using a General Oceanic® Model 2030 flowmeter. These data were used to calculate the volume of water sampled by traps (*X*). The percent river volume sampled by traps (%*Q*) was estimated by the ratio of river volume sampled to total river volume passing RBDD. River volume (*Q*) was obtained from the California Data Exchange Center's Bend Bridge gauging station (http://cdec2.water.ca.gov/cgi-progs/queryFx?bnd).

Sampling effort.—We quantified weekly rotary trap sampling effort by assigning a value of 1.00 to a sample consisting of four, 2.4-m diameter rotary-screw traps sampling 24 hours daily, seven days weekly. Weekly values <1.00 represent occasions where less than four traps were sampling, traps were structurally modified to sample only one-half the normal volume of water or when less than seven days were sampled.

Trap efficiency trials.—Fish were marked with bismark brown staining solution (Mundie and Traber 1983) prepared at a concentration of 21.0 mg/L of water. Fish were stained for a period of 45-50 minutes, removed, and allowed to recover in fresh water. Marked fish were held for 6-24 hours before being released 4 km upstream from RBDD after sunset. Recapture of marked fish was recorded for up to five days after release. Trap efficiency was calculated based on the proportion of recaptures to total fish released.

Trap efficiency modeling.—Trap efficiency (i.e., the proportion of the juvenile population passing RBDD captured by traps) was modeled with %*Q* to develop a simple least-squares regression equation. The equation was then used to calculate daily trap efficiencies based on daily river volume sampled. To model trap efficiency with %*Q*, we conducted mark-recapture trials and estimated trap efficiency during trials as noted above.

Passage estimates.—Winter Chinook passage was estimated by employing the model developed to predict daily trap efficiency ($\hat{T}_d$). The trap efficiency model was developed by conducting 129 mark/recapture trials at RBDD and used *%Q* as the primary variate (Martin et al. 2001, Poytress and Carrillo 2011). Trap efficiency estimates from trials were plotted against *%Q* to develop a least squares regression equation (eq. 5), whereby daily trap efficiencies could be predicted.

[2] Generated by Sheila Greene, California Department of Water Resources, Environmental Services Office, Sacramento (May 8, 1992) from a table developed by Frank Fisher, California Department of Fish and Game, Inland Fisheries Branch, Red Bluff (revised February 2, 1992). Fork lengths with overlapping run assignments were placed with the latter spawning run.

Daily passage ($\hat{P}_d$).—The following procedures and formulae were used to derive daily and weekly estimates of total numbers of winter Chinook salmon passing RBDD. We defined C_{di} as catch at trap i (i = 1,…,t) on day d (d = 1,…,n), and X_{di} as volume sampled at trap i (i = 1,…t) on day d (d = 1,…n). Daily salmonid catch and water volume sampled were expressed as:

1. $$C_d = \sum_{i=1}^{t} C_{di}$$

and,

2. $$X_d = \sum_{i=1}^{t} X_{di}$$

The $\%Q$ was estimated from the ratio of water volume sampled (X_d) to river discharge (Q_d) on day d.

3. $$\%\hat{Q}_d = \frac{X_d}{Q_d}$$

Total salmonid passage was estimated on day d (d = 1,…,n) by

4. $$\hat{P}_d = \frac{C_d}{\hat{T}_d}$$

where,

5. $$\hat{T}_d = (0.00720)(\%\hat{Q}_d) + 0.00145$$

and, $\hat{T}_d =$ predicted trap efficiency on day d.

Weekly passage ($\hat{P}$).—Population totals for numbers of Chinook salmon passing RBDD each week were derived from $\hat{P}_d$ where there are N days within the week:

6. $$\hat{P} = \frac{N}{n}\sum_{d=1}^{n}\hat{P}_d$$

Estimated variance.—

7. $$Var(\hat{P}) = (1-\frac{n}{N})\frac{N^2}{n}s^2_{\hat{P}_d} + \frac{N}{n}\left[\sum_{d=1}^{n}Var(\hat{P}_d) + 2\sum_{i\neq j}^{n}Cov(\hat{P}_i,\hat{P}_j)\right]$$

The first term in eq. 7 is associated with sampling of days within the week.

8. $$s^2_{\hat{P}_d} = \frac{\sum_{d=1}^{n} (\hat{P}_d - \bar{\hat{P}})^2}{n-1}$$

The second term in eq. 7 is associated with estimating $\hat{P}_d$ within the day.

9. $$Var(\hat{P}_d) = \frac{\hat{P}_d(1-\hat{T}_d)}{\hat{T}_d} + Var(\hat{T}_d)\frac{\hat{P}_d(1-\hat{T}_d)+\hat{P}_d{}^2\hat{T}_d}{\hat{T}_d^3}$$

where,

10. $$Var(\hat{T}_d) = \text{error variance of the trap efficiency model}$$

The third term in eq. 7 is associated with estimating both $\hat{P}_i$ and $\hat{P}_j$ with the same trap efficiency model.

11. $$Cov(\hat{P}_i, \hat{P}_j) = \frac{Cov(\hat{T}_i, \hat{T}_j)\hat{P}_i\hat{P}_j}{\hat{T}_i\hat{T}_j}$$

where,

12. $$Cov(\hat{T}_i, \hat{T}_j) = Var(\hat{\alpha}) + x_i Cov(\hat{\alpha}, \hat{\beta}) + x_j Cov(\hat{\alpha}, \hat{\beta}) + x_i x_j Var(\hat{\beta})$$

for some $\hat{T}_i = \hat{\alpha} + \hat{\beta} x_i$

Confidence intervals (CI) were constructed around $\hat{P}$ using eq. 13.

13. $$P \pm t_{\alpha/2, n-1}\sqrt{Var(\hat{P})}$$

Annual JPI's were estimated by summing $\hat{P}$ across weeks.

14. $$JPI = \sum_{week=1}^{52} \hat{P}$$

Winter Chinook fry (≤ 45 mm FL) and pre-smolt/smolt (≥ 46 mm FL) passage was estimated by size class. However, the ratio of fry to pre-smolt/smolts passing RBDD is variable among years, therefore, we standardized juvenile production by estimating a fry-equivalent JPI for among-year comparisons. Fry-equivalent JPI's were estimated by the summation of fry JPI's and a weighted (1.7:1) pre-smolt/smolt JPI (59% fry-topresmolt/smolt survival; Hallock undated). Rotary trap JPI's could then be directly compared to JPE's.

Hypothesis testing.— The JPI is a direct measure of juvenile production and has been used to track the JPE, an indirect measure of juvenile production (Martin et al., 2001). Juvenile production estimates derived from effective spawner populations based on the 2010 carcass surveys (Carcass JPE) were used for comparisons with the fry-equivalent JPI. The hypothesis we tested was:

H_{o1} : Carcass JPE does not differ from in-river estimates of juvenile abundance (JPI)
H_{a1} : Carcass JPE differs from in-river estimates of juvenile abundance (JPI)

We used a paired *t*-test for testing significant differences using years as replicates. We currently have twelve data points to compare with the Carcass JPE. BY 2010 data was added to the prior years' data and compared. Within-year evaluations were made by comparing Carcass JPE's with the JPI and determining whether the JPE's fall within the confidence intervals about the JPI.

Results

Sampling effort.—Weekly sampling effort throughout the 2010 brood-year emigration period was highly variable and ranged from 0.00 to 1.00 ($\bar{x}$ = 0.76, N = 52 weeks; Table 2). Weekly sampling effort ranged from 0.11 to 1.00 ($\bar{x}$ = 0.84, N = 26 weeks) between July and December, the period of greatest juvenile winter Chinook emigration, and 0.00 to 1.00 ($\bar{x}$ = 0.67, N = 26 weeks) during the latter half of the emigration period (Table 2).

Variance in sampling effort throughout the year can be attributed to several sources. They included (1) RBDD gate operations, (2) intentional reductions in effort resulting from cone modification(s), sampling < 4 traps, or unsampled days, (3) California Department of Fish and Game (CDFG) Scientific Collecting Permit restrictions for capture of Threatened green sturgeon, and (4) unintentional reductions in effort resulting from high flows and/or elevated debris loads (Figure 3). Ten of 52 weeks sampled had 3 or more different reasons why sampling effort was reduced from the maximum value of 1.00 or 28 possible samples (i.e., 4 traps sampling unmodified for 7 days).

Trap efficiency trials.—Four mark-recapture trials were conducted using naturally produced fall run fry sized Chinook during the winter of 2011 to estimate rotary-screw trap efficiency (Table 2). Sacramento River mean daily discharge sampled during the trials ranged from 5,228 to 9,516 cfs ($\bar{x}$ = 7,180 cfs). Estimated *%Q* during trap efficiency trials ranged from 3.70% to 5.44% ($\bar{x}$ = 4.60 %; Table 2).

Trials were conducted with RBDD gates raised, rotary traps unmodified, and while sampling with 4 traps (N = 4). All trials were conducted using Chinook sampled from rotary traps, and trap efficiencies ranged from 3.83 to 5.12% ($\bar{x}$ = 4.69%). The number of marked fish released per trial ranged from 1,582 to 1,989 ($\bar{x}$ = 1,750). The number of marked fish recaptured after release ranged from 61 to 109 ($\bar{x}$ = 83). All fish were released after sunset and 96% of recaptures occurred within the first 24 hours, 98% within 48 hours, 99% within 72 hours, and 100% within 96 hours. One fish was recaptured 142 hours after release during a mild storm event. Fork lengths of fish marked and released ranged from 31 to 48 mm ($\bar{x}$ = 36.6 mm). Fork lengths of recaptured marked fish ranged from 32 to 42 mm ($\bar{x}$ = 36.3 mm).

*Trap efficiency modeling.***—**Trap efficiency was positively correlated to *%Q*, with higher efficiencies occurring as river discharge volumes decreased and the proportion of discharge volume sampled by rotary-screw traps increased (Figure 4). Regression analysis revealed a significant relationship between trap efficiency and *%Q* ($P < 0.001$). The strength of the relationship was improved from that in 2009 (Poytress and Carrillo 2011) with the addition of four trials conducted during brood-year 2010 ($r^2 = 0.49$; Figure 4).

*Fork length evaluations***.—** The length frequency distribution of brood-year 2010 juveniles captured at RBDD ranged from 30 mm to 160 mm (Figure 5). Fry sized individuals ranged from 30 to 45 mm and comprised 72% of all samples collected. Pre-smolt/smolt sized individuals ≥46 mm represented the remaining 28% of brood-year 2010 winter Chinook samples.

Weekly median fork length of brood-year 2010 winter Chinook ranged from 35 to 36 mm between week 28 and 41 (Table 3). Median fork lengths increased rapidly from 41 to 86 mm between week 42 and week 2. This was followed by variability and an overall decrease between week 3 and week 5. Weekly median fork lengths generally increased thereafter to 128 mm in week 17 (Figure 6a).

*Patterns of abundance***.—**Brood-year 2010 winter Chinook juvenile passage at RBDD was 1,281,778 fry and pre-smolt/smolts combined (Table 3). Winter Chinook juvenile passage increased from 460 (week 28; mid-July) to 27,730 (week 32; mid-August). Juvenile passage during week 33 was estimated at 55,766 from a single day's sample of the week as traps were removed for RBDD operations associated with removal of Lake Red Bluff. Peak passage of winter Chinook juveniles occurred predominantly during weeks 36 through 43; the middle of September through the middle of October (Figure 6b). Juvenile passage generally declined following week 43 (November) to 7,595 with pulses of fish passage associated with winter storms (weeks 44 through week 11). Total passage between weeks 28 through 52 was 1,244,399 and accounted for 97.1% of total annual passage.

Brood-year 2010 fry sized juveniles (≤45 mm FL) comprised 68% of total winter Chinook passage (Table 3). Fry began to pass RBDD during week 28 (early-July). Weekly fry passage generally increased through week 35. The estimated peak passage of 158,892 fry sized juveniles was observed during mid-September in week 37. Fry passage remained relatively high between weeks 38 through week 43 and then steadily declined. Fry passage ceased as fish fell outside the fry size class by week 48 in December (Table 3; Figure 7b).

Brood-year 2010 pre-smolt/smolt sized juveniles (≥46 mm FL) comprised 32% of total passage and the first observed emigration past RBDD occurred in week 34 (end of August; Table 3). Weekly passage increased from 188 to 21,274 between week 34 and 42. Peak passage was observed in week 43 (October) at 128,681. Weekly passage trends generally declined thereafter through week 52. From week 1 through week 17 of 2011, juvenile winter Chinook passage diminished from the thousands to the hundreds with occasional minor peaks associated with storm and flow activity (Table 3; Figure 8b).

Comparisons of JPI and Carcass JPE. —The fry-equivalent rotary trap JPI for brood-year 2010 was 1,566,507 (Table 3). The 90% confidence intervals around the estimate were 988,163 (lower) and 2,144,851 (upper; Table 4). The NMFS brood-year 2010 fry-equivalent Carcass JPE was 1,049,385 (Table 4). In 2010, the Carcass JPE fell within the 90% CI about the rotary trap JPI exceeding the lower 90% value by approximately 61,000 juveniles (Table 4). By direct comparison of annual point estimates, the Carcass JPE was 33% less than the 2010 rotary trap JPI. The difference in numerical values equated to (-) 517,122 juvenile winter Chinook (Table 4).

We combined data from 1996 to 2009 with brood-year 2010 fry-equivalent JPI's and JPE's to evaluate the linear relationship between the estimates. Thirteen observations were evaluated using the carcass survey data as the winter Chinook carcass survey did not start until 1996 and rotary trapping at RBDD was not conducted in 2000 and 2001. Rotary trap JPI's were significantly correlated in trend to Carcass JPE's ($r^2 = 0.84$, $P < 0.001$, df = 12; Figure 9).

In terms of the magnitude of the two estimates, a paired t-test detected no significant difference among rotary trap JPI's and Carcass JPE's ($t = -0.63$, $P = 0.54$, df =12). For the combined thirteen years of data, Carcass JPE's averaged 3% greater than rotary trap JPI's (range = -37 to +62%).

Discussion

*Sampling effort***.—**During BY 2010, sampling effort was 84% during weeks 27-52 which accounted for 97% of the winter Chinook passage data collected. During the RBDD gates in period, effort was reduced by one trap for each day of sampling for weeks 27 – 32, due to regulations requiring an 18-inch opening for each open gate (NMFS 2009). This resulted in less gates being open compared to many previous years and less area to sample behind the RBDD during this period of the BY 2010 emigration. Martin et al. (2001) determined that three traps were the minimum that could sample to allow for appropriate use of the trap efficiency model. One result of sampling three versus four traps was less water volume sampled and consequently a lower daily predicted trap efficiency resulting in a relatively larger daily passage estimate. Overall, this period only accounted for a mere 3.2% of the annual passage estimate and was considered to not have a significant effect on the annual estimate.

Sampling effort during week 33 (11%; Table 1) resulted in a weekly passage estimate of 55,769 (Table 3). Traps are unable to sample this period as there is a substantial change in river stage and hydrology below the RBDD between the gates lowered and raised periods. Juvenile winter Chinook passage peaks in September through October in most years and the weekly passage estimate for week 33 accounted for 4% of the annual passage estimate.

Similar to BY 2008 and BY 2009, effort was not reduced intentionally to decrease capture of winter Chinook juveniles during the typical peak emigration period (weeks 38 - 42). Effort was 100% during this period and passage accounted for 37% of the annual estimate.

During the secondary migration period between January and June, effort was reduced between mid-March and April primarily as a result of high discharge levels from Shasta/Keswick dams for flood control operations (Figure 10a). Additionally, effort was reduced intentionally to minimize catch of fall run production fish released from Coleman National Fish Hatchery (April – May). Intentionally reduced effort occurred by sub-sampling portions of the night and day, modifying traps to sample at 50% effort, or sampling less than 4 traps (Figure 3).

Trap efficiency modeling.**—**On 4 occasions in 2011, we measured the efficiency of our rotary-screw traps by conducting mark-recapture trials using naturally produced fish collected during trap sampling activities (Table 2). Data from the 4 trials were combined with data from 125 previously conducted trials to model the relationship between trap efficiency and %Q at RBDD (Figure 4). Trap efficiency was moderately correlated with %Q ($r^2 = 0.49$), yet regression Analysis of Variance continues to indicate a highly significant relationship exists between model variables ($P< 0.001$, df = 128). Overall, the correlation was improved over that reported in Poytress and Carrillo (2011) by 7%.

Patterns of abundance.**—**Brood-year 2010 winter Chinook juvenile passage at RBDD from July 1, 2010 through June 30, 2011 was 1,281,778 fry and pre-smolt/smolts combined. The 2010 total passage estimate was made up of 68% fry (875,023) and 32% pre-smolt/smolts (406,755; Table 3).

Peak passage, representing 71% of the annual total estimate, occurred within an eight week period from mid-September through late-October (Figure 6b). Between October and the end of December (week 42 – week 52), the first storm events of the fall season produced significant increases in discharge volume and increased turbidity (Figure 10 a, b). The first storm event in late-October resulted in a very high increase in turbidity from 2 NTU to 76 NTU (data point obtained from CDEC Bend Bridge gauging station as peak was not sampled; Figure 10b). As a result, a substantial increase of fry and pre-smolt/smolt winter Chinook passage occurred (Table 3; Figure 6b & 8b) translating into a weekly passage value comprising 32% of total pre-smolt/smolt passage for the year. Moreover, total passage for that week accounted for 15% of the annual total passage estimate and appeared driven by the discharge and turbidity change.

In comparison to brood-year 2007, estimated juvenile passage was 12% less in 2010 representing a juvenile cohort replacement rate of 0.88 (Poytress and Carrillo 2010). The winter Chinook adult return of 2010 was not improved over the returns seen in 2007 (USFWS 2008, USFWS 2011).

Egg to Fry Survival Rates.—The estimated number of females spawning in the Sacramento River in 2010 was 53.6% of that estimated in 2007, yet the fry-equivalent production values were within 100,000 juveniles (Table 4). Barring highly variable habitat conditions in the Sacramento River within the last three years, which seems unlikely given the highly regulated river system (e.g., flow, temperature and gravel augmentation), this raises some question as to the accuracy of JPE's *and* JPI's. The NMFS JPE model, assumes no variability in survival of recruits by using an average survivorship value of 25% from estimated eggs in the river to fry leaving the spawning grounds. Conversely, the USFWS JPI is calculated based on directly measuring juveniles emigrating downstream of the spawning grounds (Martin et al. 2001). Both estimates are subject to measurement error, yet only the JPE has the potential to compound error resultant from carcass survey data. Furthermore, estimated number of eggs per female derived from Livingston Stone Winter Chinook Propagation Hatchery data is directly input into the JPE model without consideration of rates of fertilization, embryo and alevin survival (Beacham and Murray 1990), or spawning efficiency (Wales and Coots 1955) which assumedly varies annually. Compounding this error with a static egg to fry survival rate simply allows more possible routes of error introduction than the JPI which only introduces error related to the percent of volume sampled (i.e., dependent variable in the daily trap efficiency model).

As noted by Dumas and Marty (2006) for Atlantic salmon (*Salmo salar*) survival to the fry stage can vary between redds from 0 to 90% and mean survival varies from 2% to 35%. For Pacific salmonids, Wales and Coots (1955) study results of Chinook salmon in Fall Creek, CA, estimated egg to fry survival between 7 and 32%, averaging 15%. Direct observation using the JPI estimate resulted in an egg to fry survival rate of 37.3% in 2010 (Table 5). This is above that reported for Fall Creek and in excess of one standard deviation of the average survival rate of 25.2% calculated from JPI's, carcass survey derived females, and potential egg deposition (Bradford 1994) data derived from annual spawning records at Livingston Stone National Fish Hatchery (Table 5). Interestingly, the 13-year *average* value is identical to the 25% static value input into the NMFSJPE model, which was derived from estimates of fall Chinook outmigrants from the Tehama-Colusa Fish Facility artificial spawning channels in the upper Sacramento River between 1975 and 1980 (TCFF Annual reports 1975-1980).

Assuming the 2010 egg to fry survival rate measured by the JPI was correct, a number of potential reasons as to why such a high survivorship in 2010 may have occurred. These could include a lack of density dependent factors for spawners, utilization of high quality spawning sites by a low number of spawners, and or high rates of egg and alevin survival (Beacham and Murray 1990). Moreover, it may be inequitable to compare fall run spawning efficiency (Wales and Coots 1955) to winter run because flow regulated systems appear to result in significant increases in egg survival (Groot and

Margolis 1991). Winter run Chinook salmon spawning in the highly regulated (e.g., flow, temperature and gravel augmentation) Sacramento River system should, at times, result in very high levels of recruitment success or spawning efficiency in the absence of density dependent factors. Conversely, if the 2010 JPI point estimate seems unreasonably high, the use of the lower 90% confidence interval value would result in an egg to fry survival rate of 24% (Table 5), which is similar to the thirteen-year average and the NMFS JPE model static value of 25% egg to fry survival.

The value of confidence intervals around point estimates for the management of endangered winter Chinook cannot be overstated. Knowledge of the degree to which estimate uncertainty exists should result in fishery and water operations managers being able to make better resource decisions with less tenuous data. Most appropriate for management of the water and biological resources of the Sacramento system may be to simply input an annual estimate of survival to RBDD (i.e., those leaving the spawning grounds), with confidence intervals indicating a level of uncertainty. Furthermore, conduct specific research as to winter Chinook survival in lower reaches of the river through coded-wire tagging of naturally produced fry at RBDD to better estimate survival to and through the Sacramento-San Joaquin Delta system.

Comparisons of JPI's and JPE's.—Rotary-screw trap JPI's and Carcass JPE's have and continue to be strongly correlated ($r^2 = 0.84$, $P < 0.001$, df = 12; Figure 9). The 2010 Carcass JPE was 33% less than the rotary trap JPI (Table 4), but fell within the bounds of the rotary trap JPI 90% confidence intervals. Significant differences in the magnitude of JPI's and Carcass JPE's were not detected with the addition of 2010 data ($t = -0.63$, $P = 0.54$, df = 12). We therefore accept the hypothesis for the cumulative 13 years of data that carcass JPE's do not significantly differ from in-river estimates of juvenile abundance (JPI's).

Overall, the relationship between the direct measure of juvenile abundance (JPI) and the indirect or modeled approach using carcass survey data (JPE) remains strong. The addition of the 2010 data continues to support this relationship, but as noted above, the inclusion of a measure of uncertainty due to annual variability in the system should be considered to better manage water resources and protect endangered winter Chinook salmon.

Acknowledgments

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Tables

Table 1.—Annual summary of weekly rotary trap sampling effort. Full sampling effort was indicated by assigning a value of 1.00 to a week consisting of four, 2.4 m diameter rotary-screw traps sampling 24 hours daily, seven days a week. The juvenile winter Chinook brood-year (BY) is identified as beginning on July 1 and ending on June 30.

Sampling effort			
Week	BY 2010	Week	BY 2010
27 (Jul)	0.75	1 (Jan)	1.00
28	0.75	2	0.86
29	0.75	3	1.00
30	0.75	4	1.00
31 (Aug)	0.75	5 (Feb)	1.00
32	0.75	6	0.89
33	0.11	7	1.00
34	0.75	8	0.96
35 (Sep)	1.00	9 (Mar)	0.89
36	1.00	10	0.86
37	1.00	11	0.82
38	1.00	12	0.00
39	1.00	13 (Apr)	0.00
40 (Oct)	1.00	14	0.43
41	1.00	15	0.43
42	1.00	16	0.43
43	0.86	17	0.29
44 (Nov)	1.00	18 (May)	0.38
45	0.96	19	0.79
46	1.00	20	0.86
47	0.96	21	0.86
48 (Dec)	1.00	22 (Jun)	0.91
49	0.86	23	0.54
50	0.57	24	0.57
51	0.57	25	0.32
52	0.69	26	0.43

Table 2.— Summary of results from mark-recapture trials conducted in 2011 (N = 4) to evaluate rotary-screw trap efficiency at Red Bluff Diversion Dam (RK 391), Sacramento River, California. Results include the number of fish released, the mean fork length at release (Release FL), the number recaptured, the mean fork length at recapture (Recapture FL), combined 4 trap efficiency (TE %), percent river volume sampled by rotary-screw traps (%Q), number of traps sampling during trials, modification status as to whether or not traps were structurally modified to reduce volume sampled by 50% (Traps modified), and RBDD gate configuration at the time of the trial.

Trial#	Year	Number released	Release FL (mm)	Number recaptured	Recapture FL (mm)	TE (%)	%Q	Number of traps sampling	Traps modified	RBDD Gate Configuration
1	2011	1,834	36.9	79	36.0	4.31	3.70	4	No	Raised
2	2011	1,989	37.5	109	36.0	5.48	4.36	4	No	Raised
3	2011	1,593	36.4	61	36.0	3.83	4.91	4	No	Raised
4	2011	1,582	35.7	81	37.4	5.12	5.44	4	No	Raised

Table 3.— Weekly passage estimates, median fork length and juvenile production indices (JPI's) for winter Chinook salmon passing Red Bluff Diversion Dam (RK 391) for the period July 1, 2010 through June 30, 2011 (Brood-year 2010). Results include estimated passage (Est. passage) for fry (< 46 mm FL), pre-smolt/smolts (> 45 mm FL), total (fry and pre-smolt/smolts combined) and fry-equivalents. Fry-equivalent JPI's were generated by weighting pre-smolt/smolt passage by the inverse of the fry-to-pre-smolt/smolt survival rate (59% or approximately 1.7:1, Hallock undated).

Brood-year 2010

	Fry		Pre-smolt/smolts		Total		Fry-equivalents
Week	Est. passage	Med FL	Est. passage	Med FL	Est. passage	Med FL	JPI
27 (Jul)	0	-	0	-	0	-	0
28	460	35	0	-	460	35	460
29	1,130	36	0	-	1,130	36	1,130
30	1,757	36.5	0	-	1,757	36.5	1,757
31 (Aug)	11,105	37	0	-	11,105	37	11,105
32	27,730	36	0	-	27,730	36	27,730
33	55,766	36	0	-	55,766	36	55,766
34	12,110	36	188	46	12,298	37	12,430
35 (Sep)	32,639	36	326	49.5	32,965	36	33,193
36	79,547	36	564	49	80,111	36	80,506
37	158,892	36	1,615	48.5	160,507	36	161,637
38	72,867	36	1,268	53	74,135	36	75,022
39	96,248	36	5,487	52	101,736	36	105,577
40 (Oct)	130,696	36	7,659	52	138,355	36	143,716
41	88,838	36	19,035	54	107,873	36	121,198
42	32,531	36	21,274	55	53,806	41	68,698
43	65,747	40	128,681	55	194,428	51	284,505
44 (Nov)	1,885	42	5,710	57	7,595	54	11,592
45	4,188	43	51,308	58	55,496	57	91,411
46	680	44	29,655	61	30,335	61	51,093
47	100	44	18,293	63	18,392	63	31,197

Table 3.— (continued)

Week	Fry		Pre-smolt/smolts		Total		Fry-equivalents
	Est. passage	Med FL	Est. passage	Med FL	Est. passage	Med FL	JPI
48 (Dec)	109	45	22,182	63	22,291	63	37,819
49	0	-	16,851	65	16,851	65	28,646
50	0	-	16,566	68	16,566	68	28,163
51	0	-	14,799	66.5	14,799	66.5	25,159
52	0	-	7,907	70	7,907	70	13,442
1 (Jan)	0	-	13,808	76	13,808	76	23,473
2	0	-	3,155	86	3,155	86	5,364
3	0	-	4,451	76	4,451	76	7,567
4	0	-	4,025	87	4,025	87	6,842
5 (Feb)	0	-	211	70	211	70	358
6	0	-	430	96.5	430	96.5	731
7	0	-	2,120	103	2,120	103	3,604
8	0	-	1,325	103	1,325	103	2,252
9 (Mar)	0	-	1,819	105	1,819	105	3,093
10	0	-	2,068	103	2,068	103	3,515
11	0	-	2,026	115.5	2,026	115.5	3,444
12	0	-	0	-	0	-	0
13 (Apr)	0	-	0	-	0	-	0
14	0	-	1,527	109	1,527	109	2,597
15	0	-	282	117.5	282	117.5	480
16	0	-	0	-	0	-	0
17	0	-	139	128	139	128	236
18 (May)	0	-	0	-	0	-	0
19	0	-	0	-	0	-	0
20	0	-	0	-	0	-	0
21	0	-	0	-	0	-	0
22 (Jun)	0	-	0	-	0	-	0
23	0	-	0	-	0	-	0

Table 3.— (continued)

	Fry		Pre-smolt/smolts		Total		Fry-equivalents
Week	Est. passage	Med FL	Est. passage	Med FL	Est. passage	Med FL	JPI
24	0	-	0	-	0	-	0
25	0	-	0	-	0	-	0
26	0	-	0	-	0	-	0
BY Total	875,023		406,755		1,281,778		1,566,507

Table 4.—Comparisons between juvenile production estimates (JPE) and rotary trapping juvenile production indices (JPI). Carcass survey JPE's were derived from the estimated adult female escapement from the upper Sacramento River winter Chinook carcass survey. From BY95 through BY99, assumptions used in the carcass survey based NOAA Fisheries JPE model were as follows: (1) 5% pre-spawning mortality, (2) 3,859 ova per female, (3) 0% loss due to high water temperature, and (4) 25% egg-to-fry survival. From BY00 through BY10, assumptions 1-3 were estimated using carcass survey data gathered on the spawning grounds, from Livingston Stone National Fish Hatchery spawning records, and aerial redd surveys, respectively. Dashes (-) indicate no survey conducted.

	Rotary-trapping [a]			Carcass survey [b]	
		90% C.I.			
Brood-year	Fry-equivalent JPI	Lower	Upper	Fry-equivalent JPE	Female Spawners
1995	1,816,984	1,658,967	2,465,169	-	-
1996	469,183	384,124	818,096	550,872	571
1997	2,205,163	1,876,018	3,555,314	1,386,346	1,437
1998	5,000,416	4,617,475	6,571,241	4,676,143	4,847
1999	1,366,161	1,052,620	2,652,305	1,490,249	1,626
2000	-	-	-	4,946,418	5,397
2001	-	-	-	5,643,635	4,827
2002	8,205,609	4,287,999	12,162,377	6,964,626	5,670
2003	5,826,672	4,091,200	7,563,240	6,181,925	5,179
2004 [c]	3,758,790	2,673,168	4,846,169	2,786,832	3,185
2005	8,941,241	6,024,027	12,034,853	12,109,474	8,807
2006	7,301,362	4,891,041	9,706,610	11,818,006	8,626
2007	1,642,575	1,058,274	2,226,877	1,864,521	1,517
2008	1,371,735	858,304	1,885,166	1,952,614	1,443
2009	4,993,787	2,757,558	7,230,016	3,728,444	2,702
2010	1,566,507	988,163	2,144,851	1,049,385	813

[a] Rotary trap fry equivalent JPI generated by summing fry passage at RBDD with a weighted pre-smolt/smolt passage estimate. Pre-smolt/smolts were weighted by approximately 1.7 (59% fry to pre-smolt/smolt survival; Hallock undated).

[b] Carcass survey JPE using estimated effective spawner population from Snider et al. (1996-2000) and Bruce Oppenheim (2000-2011), NOAA Fisheries pers comm.

[c] The 2004 JPE calculations used a standard value of fecundity of 3,500 eggs/female (Bruce Oppenheim 2006, NOAA Fisheries, pers. comm..).

Table 5.—Summary of estimated egg to fry (ETF) survival rates derived from winter Chinook carcass survey female escapement estimates, estimates of the number of eggs per female (potential egg deposition), and the RBDD rotary trapping fry-equivalent JPI. Lower and upper 90% confidence intervals (L90 CI: U90 CI) and associated estimates of rates of egg to fry survival in parentheses. Dashes (-) indicate no survey was conducted.

Brood-year	Female Spawners [a]	Potential Egg Deposition [b]	Fry-equivalent JPI [c]	(L90 CI : U90 CI)	Estimated Recruits/Female	ETF Survival Rate (%) (L90 CI: U90 CI)
1996	571	3,859	469,183	(384,124 : 818,096)	822	21.3 (17.4 : 37.1)
1997	1,437	3,859	2,205,163	(1,876,018 : 3,555,314)	1,535	39.8 (33.8 : 64.1)
1998	4,847	3,859	5,000,416	(4,617,475 : 6,571,241)	1,032	26.7 (24.7 : 35.1)
1999	1,626	3,859	1,366,161	(1,052,620 : 2,652,305)	840	21.8 (16.8 : 42.3)
2000	-	-		-	-	-
2001	-	-		-	-	-
2002	5,670	4,923	8,205,609	(4,287,999 : 12,162,377)	1,447	29.4 (15.4 : 43.6)
2003	5,179	4,854	5,826,672	(4,091,200 : 7,563,240)	1,125	23.2 (16.3 : 30.1)
2004	3,185	5,515	3,758,790	(2,673,168 : 4,846,169)	1,180	21.4 (15.2 : 27.6)
2005	8,807	5,500	8,941,241	(6,024,027 : 12,034,853)	1,015	18.5 (12.4 : 24.8)
2006	8,626	5,484	7,301,362	(4,891,041 : 9,706,610)	846	15.4 (10.3 : 20.5)
2007	1,517	5,112	1,642,575	(1,058,274 : 2,226,877)	1,083	21.2 (13.6 : 28.7)
2008	1,443	5,424	1,371,735	(858,304 : 1,885,166)	965	17.8 (11.0 : 24.1)
2009	2,702	5,519	4,993,787	(2,757,558 : 7,230,016)	1,848	33.5 (18.5 : 48.5)
2010	813	5,161	1,566,507	(988,163 : 2,144,851)	1,927	37.3 (23.6 : 51.1)
				Average	**1,205**	**25.2 (7.6 : 36.7)**
				Standard Deviation	**372**	**7.7 (6.5 : 12.7)**

[a] Carcass survey derived estimated effective spawner population from Snider et al. (1996-2000) and Bruce Oppenheim (2000-2011), NOAA Fisheries pers comm.

[b] Egg estimates derived from Coleman National Fish Hatchery average of 76 females spawned in 1995, for the years 1996-1999. Data for 2002 – 2010 derived from annual average egg counts of winter run brood stock spawned at the Livingston Stone National Fish Hatchery.

[c] Rotary trap fry equivalent JPI generated by summing fry passage at RBDD with a weighted pre-smolt/smolt passage estimate. Pre-smolt/smolts were weighted by approximately 1.7 (59% fry to pre-smolt/smolt survival; Hallock undated).

Figures

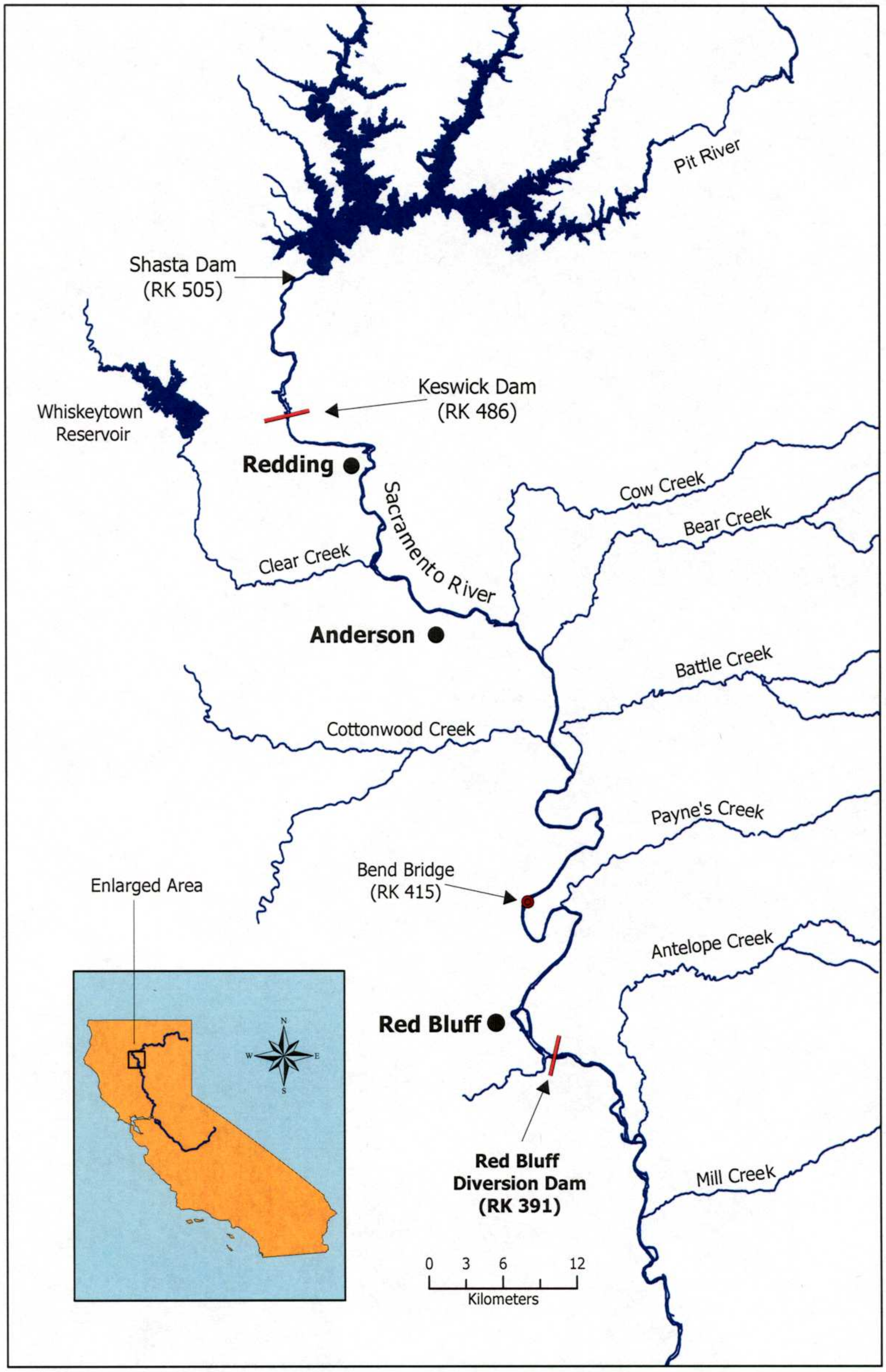

Figure 1. Location of Red Bluff Diversion Dam on the Sacramento River, California at river kilometer 391 (RK 391).

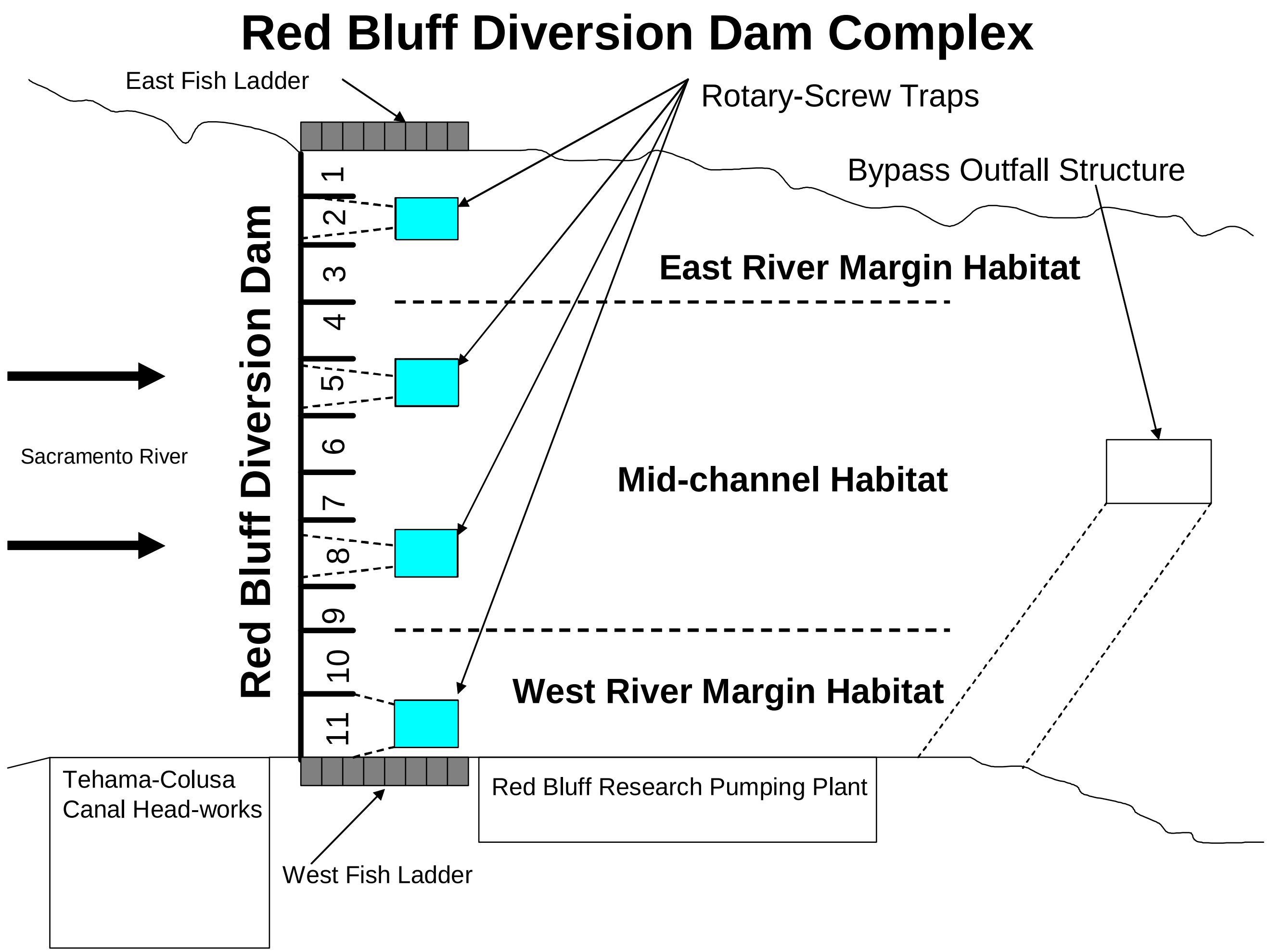

Figure 2. Rotary-screw trap sampling transect at Red Bluff Diversion Dam Complex (RK391) on the Sacramento River, California.

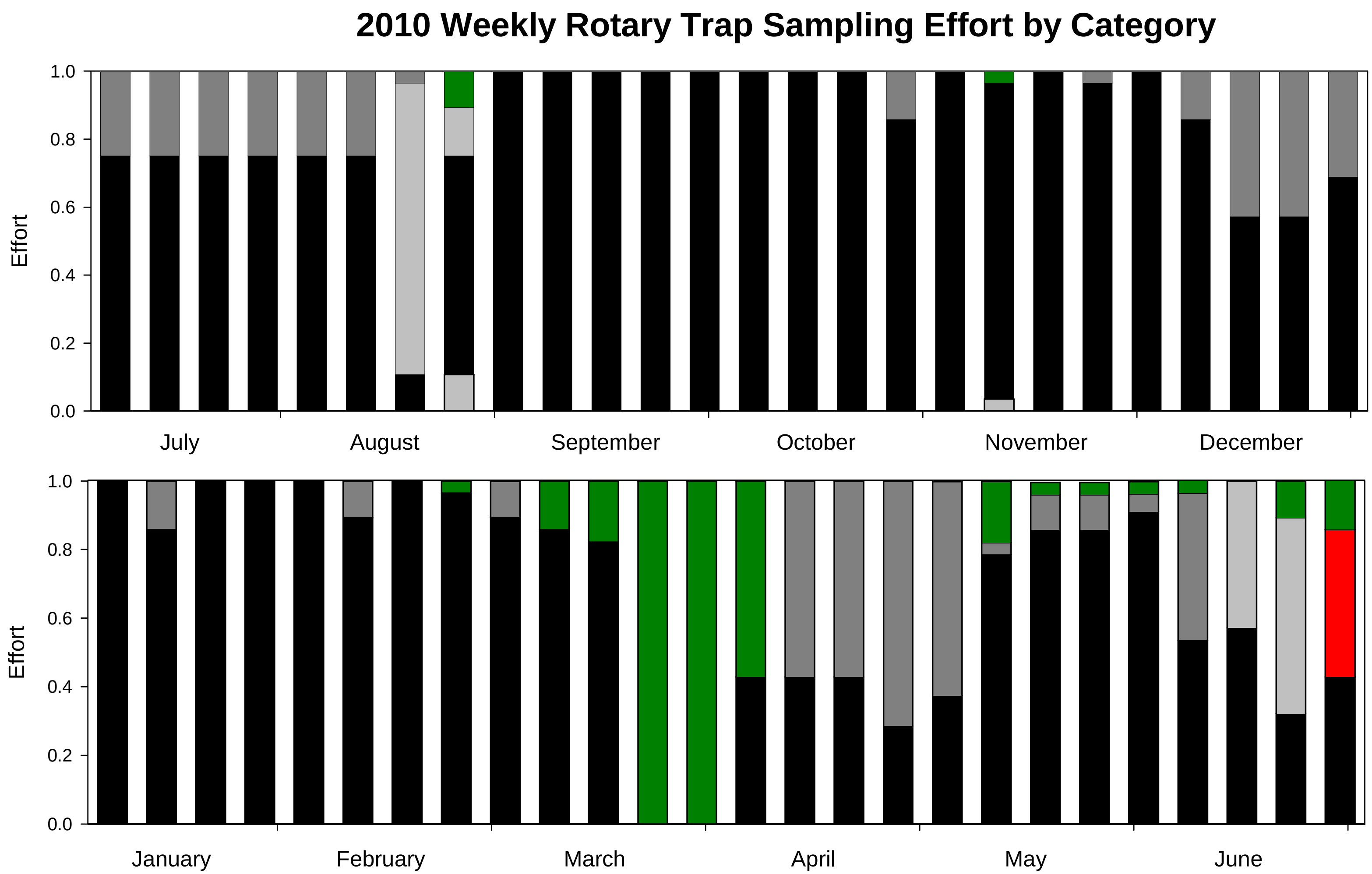

Figure 3. Weekly (bars) and monthly rotary trap sampling effort for the period July 1, 2010 through June 30, 2011 by category. Sampled portions represented by black bars; unsampled portions designated in descending order of frequency: intentional reductions in effort (dark grey), RBDD operations (light grey), unintentional reductions (dark green) and CDFG permit restrictions (red).

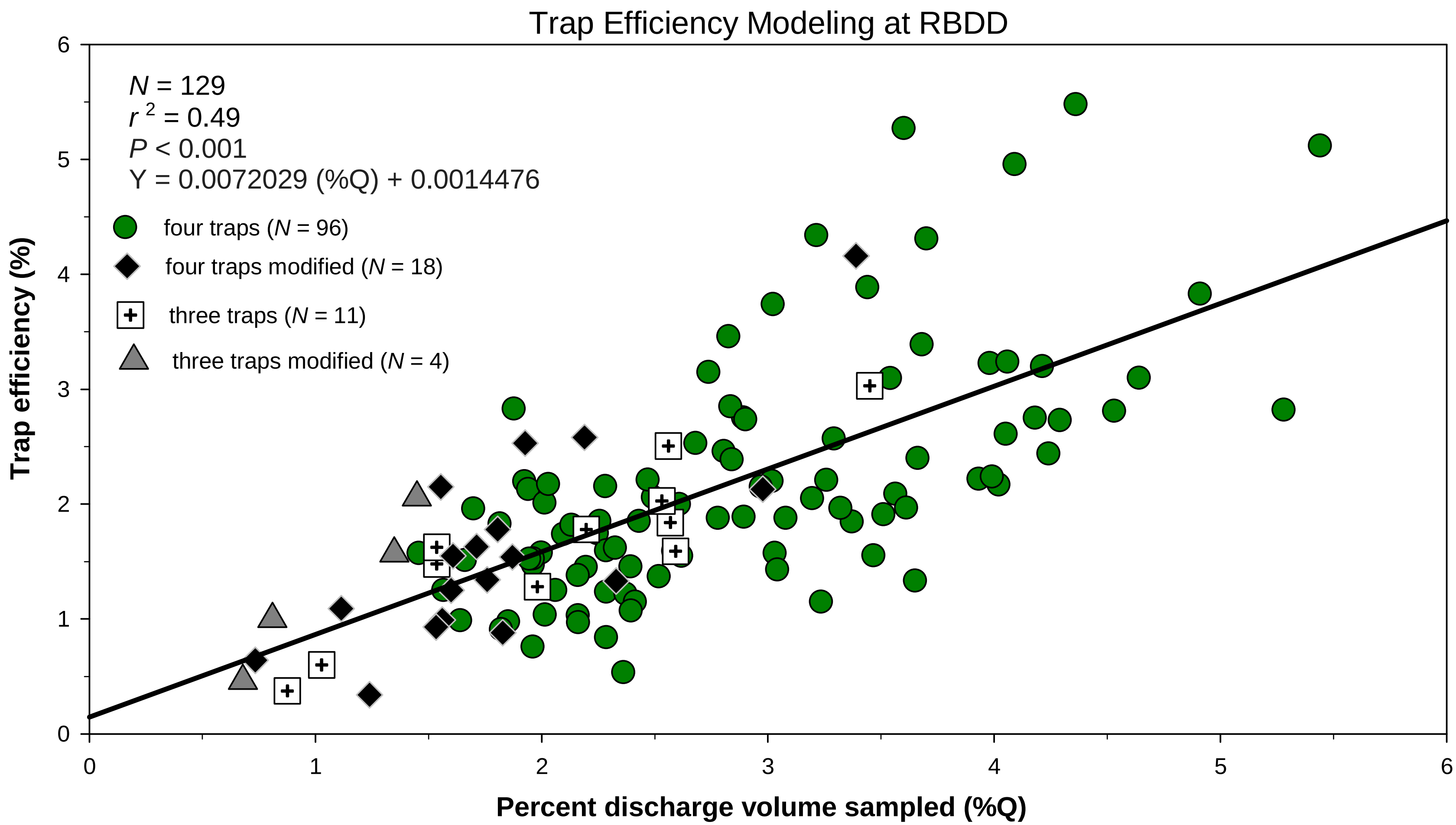

Figure 4. Trap efficiency model for combined 2.4 m diameter rotary-screw traps at Red Bluff Diversion Dam (RK 391), Sacramento River, CA. Mark-recapture trials were used to estimate trap efficiencies and trials were conducted using either four traps (N = 96), three traps (N = 11), or with traps modified to sample one-half the normal volume of water (N = 22).

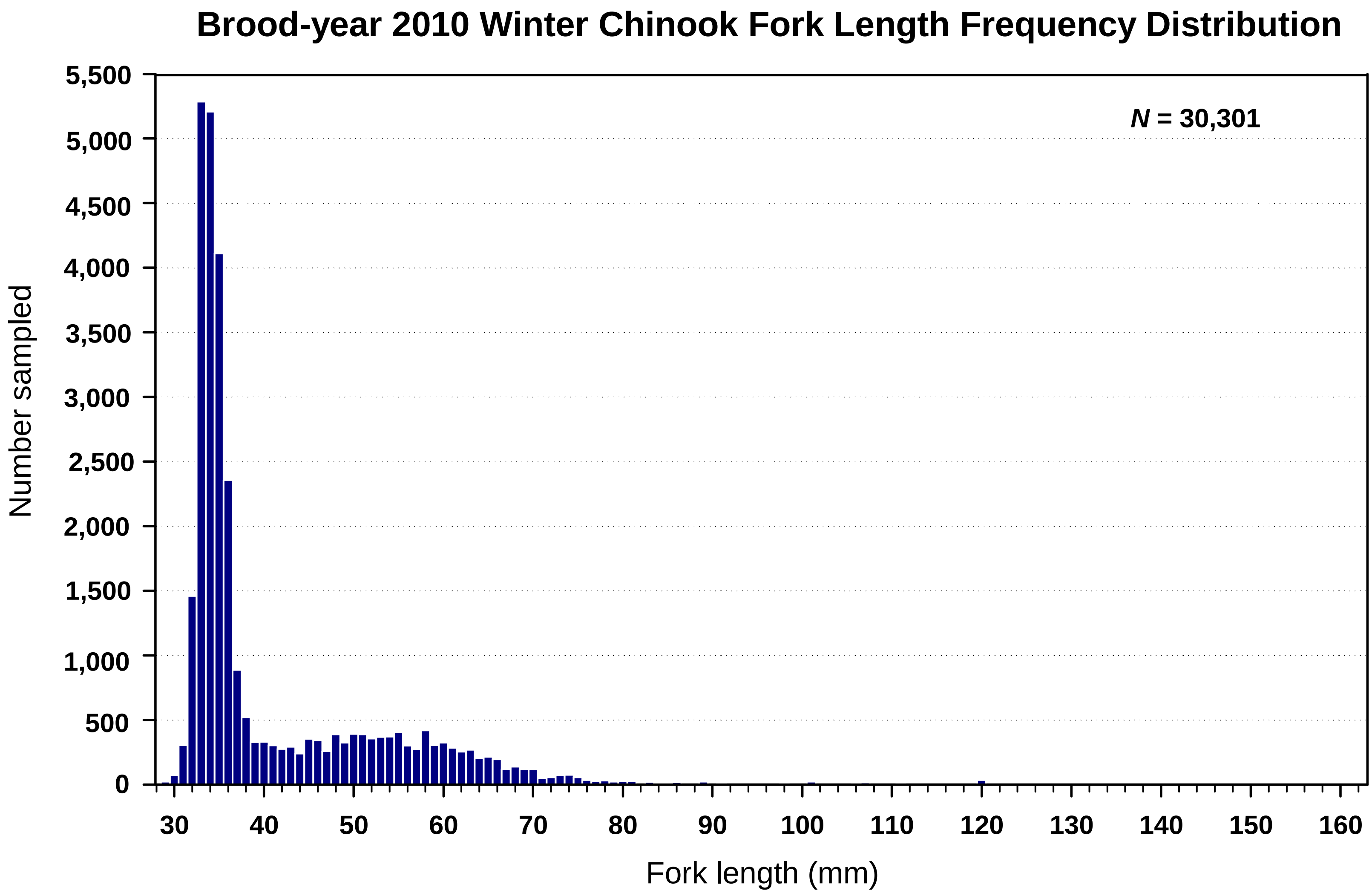

Figure 5. Fork length frequency distribution of brood-year 2010 juvenile winter Chinook salmon sampled by rotary-screw traps at Red Bluff Diversion Dam (RK 391), Sacramento River, California. Fork length data was expanded to unmeasured individuals when sub-sampling protocols were implemented. Sampling was conducted from July 1, 2010 through June 30, 2011.

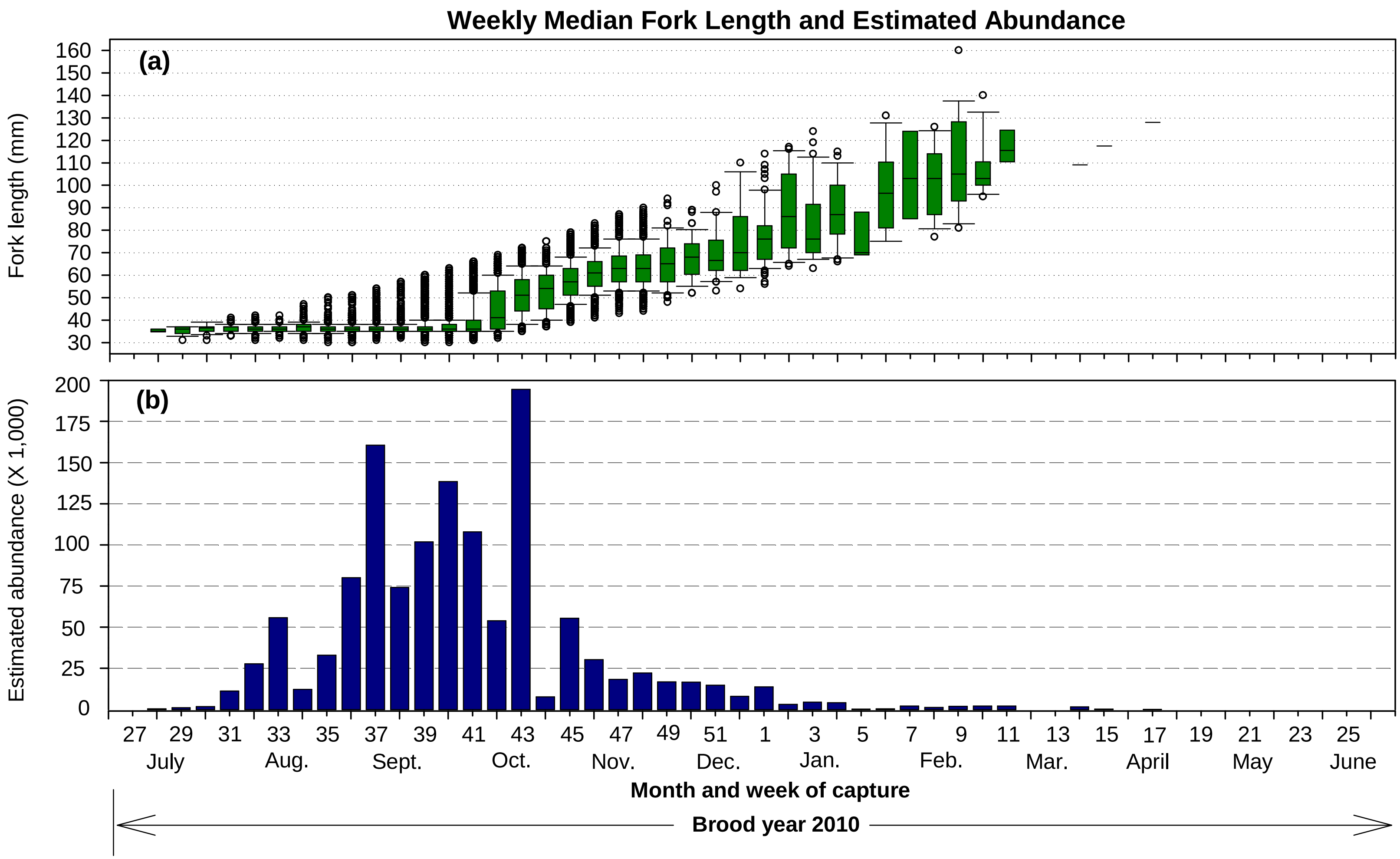

Figure 6. Weekly median fork length (a) and estimated abundance (b) of juvenile winter Chinook salmon passing Red Bluff Diversion Dam (RK 391), Sacramento River, California. Winter Chinook juveniles were sampled by rotary-screw traps for the period July 1, 2010 through June 30, 2011. Box plots display weekly median fork length, 10th, 25th, 75th, and 90th percentiles and outliers.

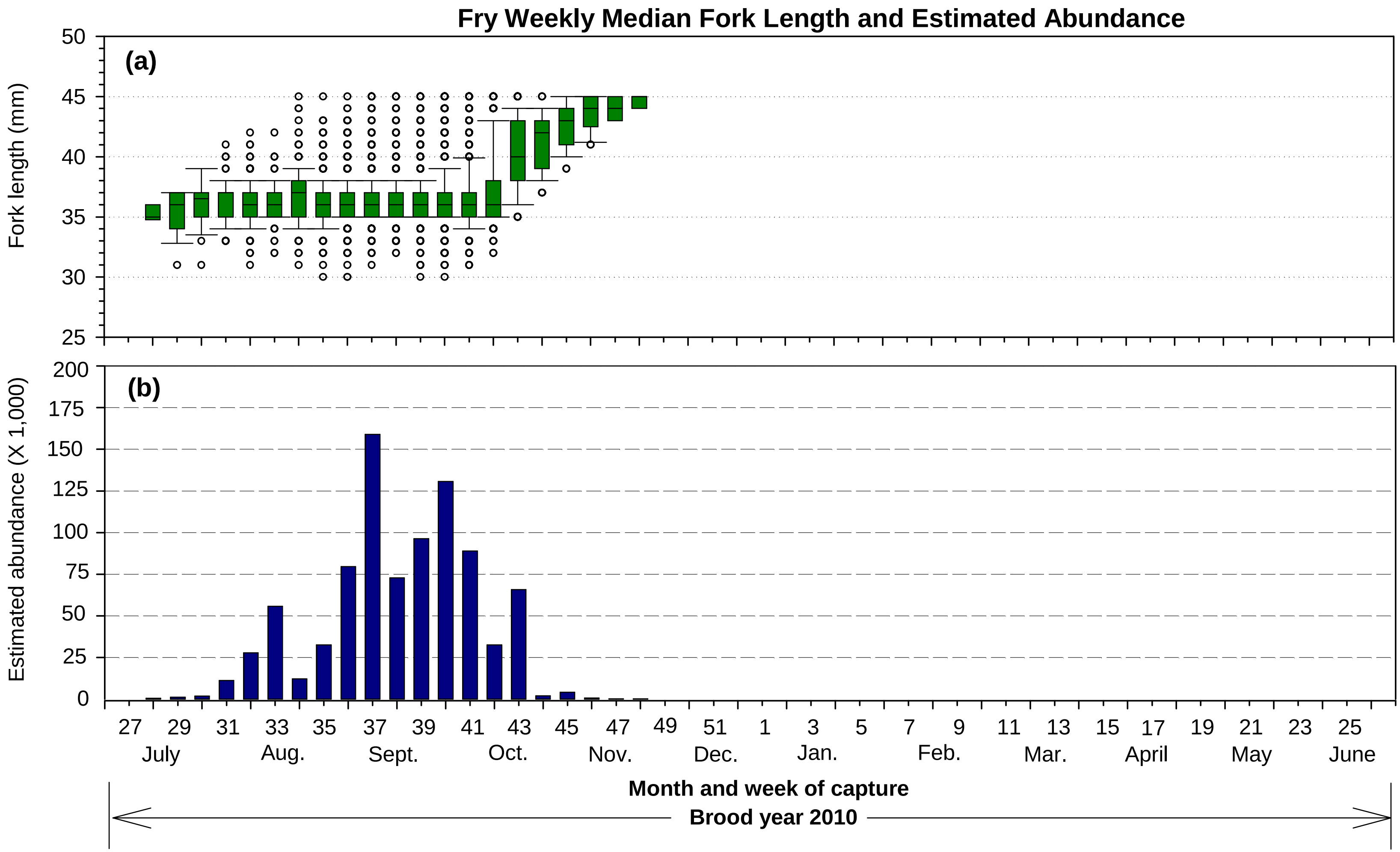

Figure 7. Weekly median fork length (a) and estimated abundance (b) of winter Chinook salmon fry passing Red Bluff Diversion Dam (RK 391), Sacramento River, California. Winter Chinook juveniles were sampled by rotary-screw traps for the period July 1, 2010 through June 30, 2011. Box plots display weekly median fork length, 10th, 25th, 75th, and 90th percentiles and outliers.

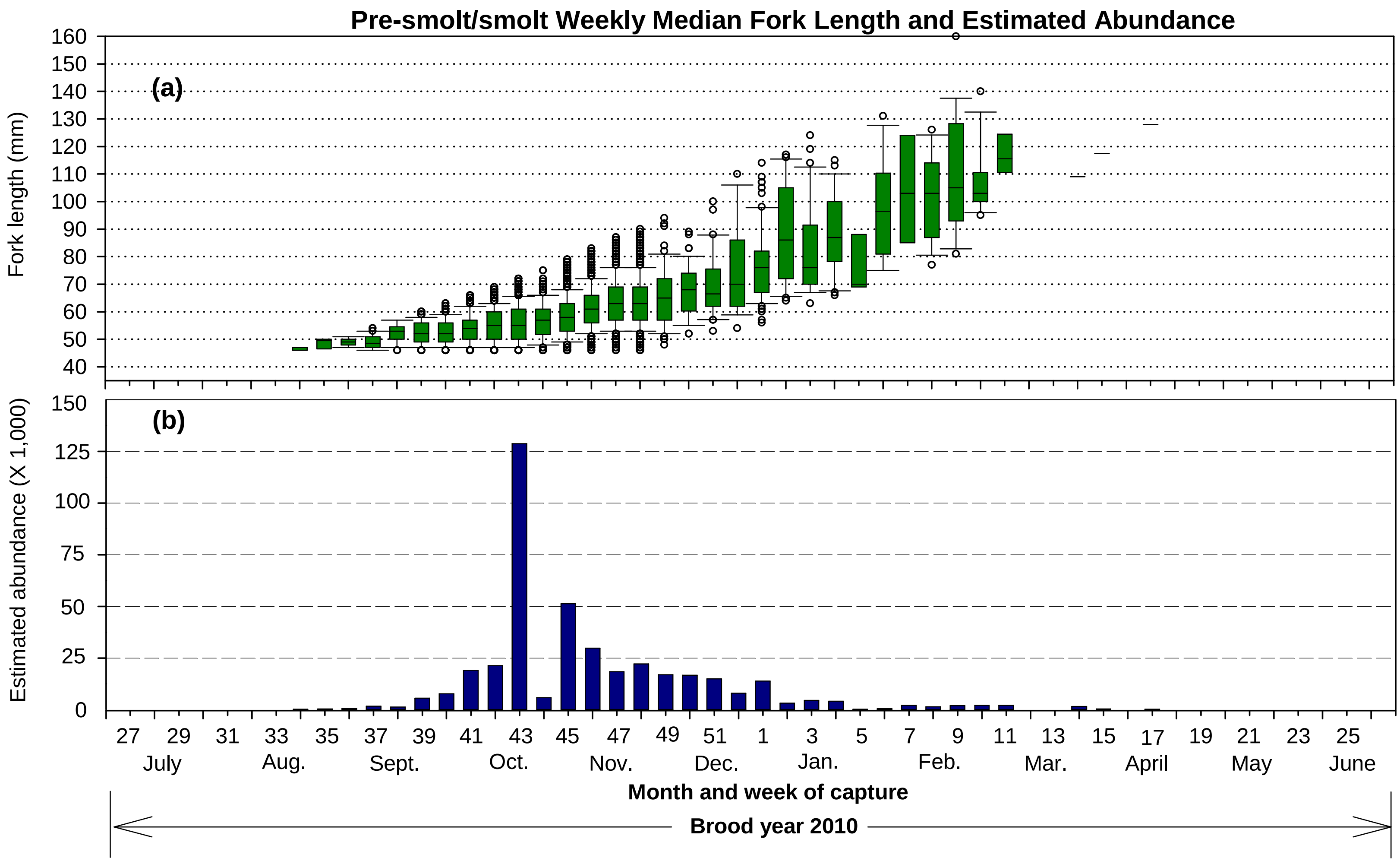

Figure 8. Weekly median fork length (a) and estimated abundance (b) of winter Chinook pre-smolt/smolts passing Red Bluff Diversion Dam (RK 391), Sacramento River, California. Winter Chinook juveniles were sampled by rotary-screw traps for the period July 1, 2010 through June 30, 2011. Box plots display weekly median fork length, 10th, 25th, 75th, and 90th percentiles and outliers

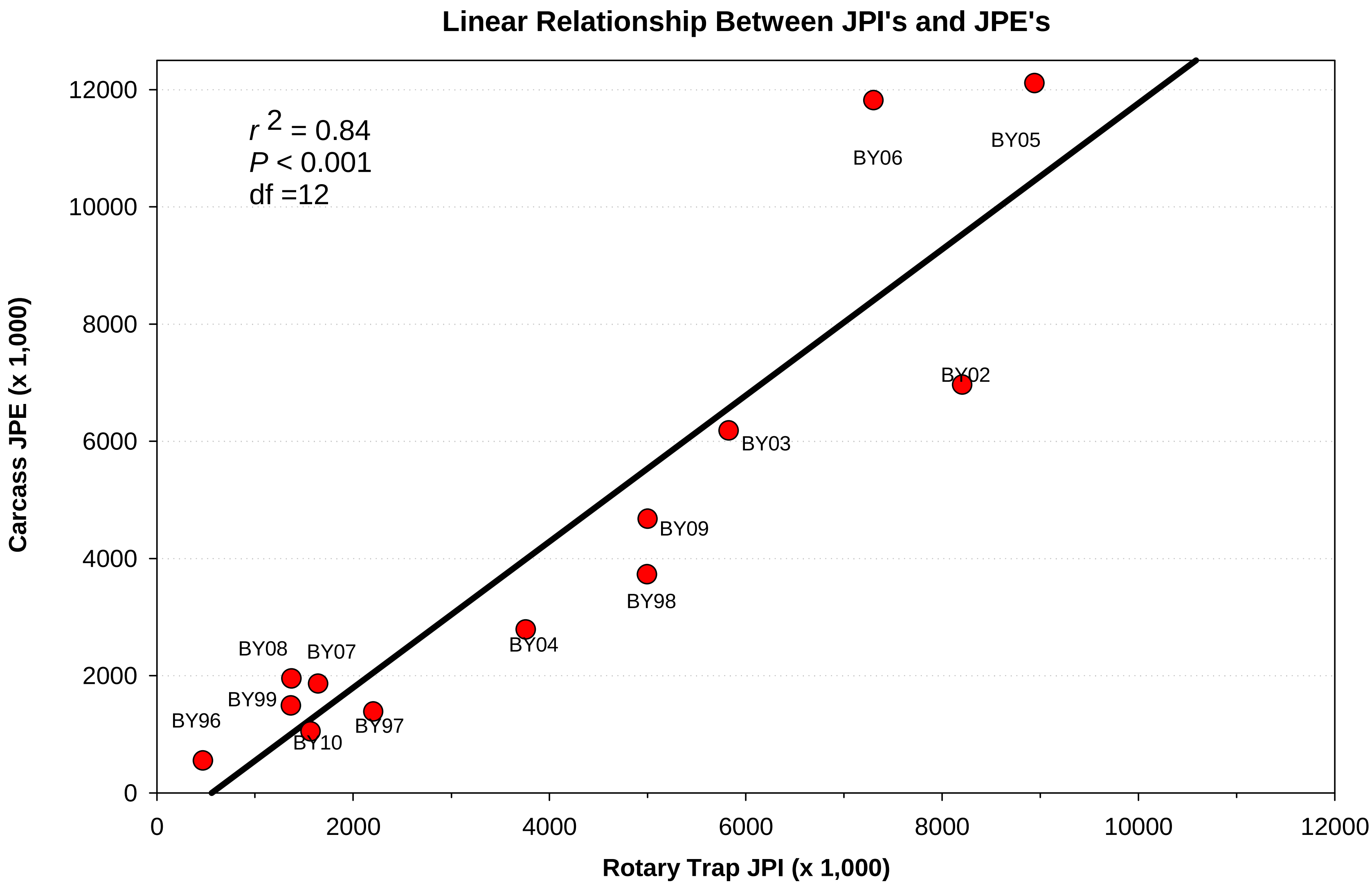

Figure 9. Linear relationship between rotary-screw trap fry-equivalent juvenile production indices (Rotary Trap JPI) and carcass survey derived juvenile production estimates (Carcass JPE).

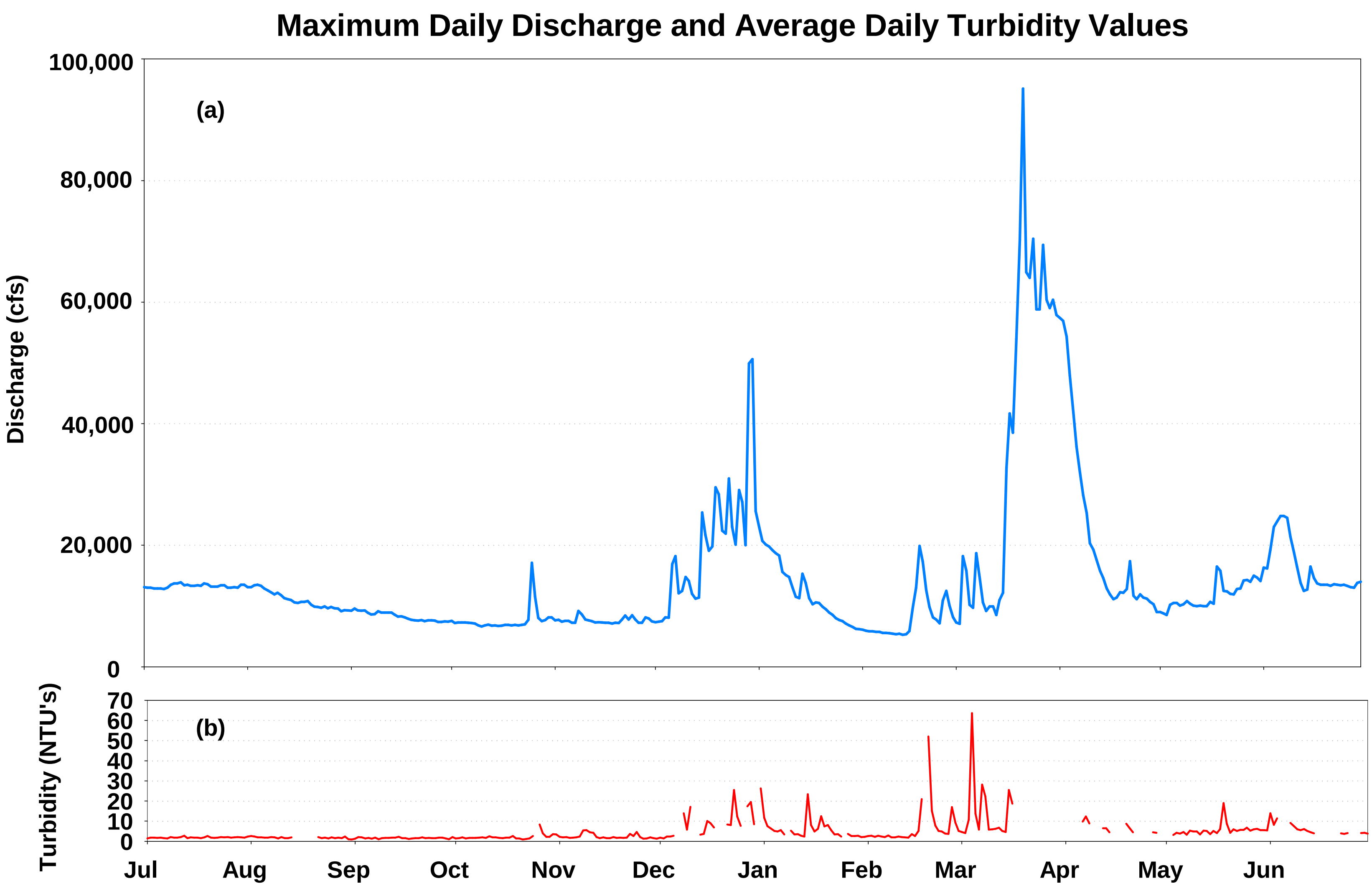

Figure 10. Maximum daily discharge (a) calculated from the California Data Exchange Center's Bend Bridge gauging station and average daily turbidity values (b) from rotary-screw traps at RBDD for the period July 1, 2010 through June 30, 2011.